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Using MHD Simulation For Space Weather Forecasting and Nowcasting	F49620-99-1-0053
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Maryland Department of Astronomy College Park, MD 20742	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NM 4015 Wilson Blvd, Room 713 Arlington, VA 22203-1954	10. SPONSORING/MONITORING AGENCY REPORT NUMBER F49620-99-1-0053
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13. ABSTRACT *(Maximum 200 words)*

In this three year project, we have investigated the feasibility of using the Lyon-Fedder-Moharry (LFM) code to predict in real time space weather conditions and display these conditions through diagnostics tailored for the use of NOAA and Air Force operators. We have performed numerous simulations of diverse space weather events including magnetic storms and substorms using as input solar wind and IMF data from the WIND and ACE spacecraft. We have validated these results against spacecraft and ground based observations both in our own studies and through participation in community code metrics studies. We have also developed diagnostics for space weather operators that display the simulation results effectively and meaningfully. We have consulted frequently with our colleagues at the NOAA Space Environment Center throughout the project to get their evaluation of the diagnostics and presented them in papers each year at the Space Weather Week meeting they host.

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FINAL REPORT – FY 1999 - 2001

Instructions: Provide all information identified below for the last FY only. List Research Objectives in bullet format. Provide Summary of Progress and Forecast for next FY in narrative format.

Research Title: Using MHD Simulation for Space Weather Forecasting and Nowcasting

Principal Investigator: Charles C, Goodrich

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AFOSR Program Manager: Major Paul Bellaire, Jr.

Research Objectives:

Investigate the feasibility of using the Lyon-Fedder-Mobarry (LFM) global MHD for Space Weather forecasting. Specific goals include:

- **Validation:** Using real time ACE and WIND data, use metrics to quantitatively measure the code's accuracy for long duration runs
  - Strength and location of the ionospheric electrojets
  - Location of the dayside magnetopause
  - Radiation belt electron flux
- **Indicators**: Develop and test with operators key indicators for the ionospheric electrojet, magnetopause, and radiation belt conditions
- **Input data Sensitivity**: Investigate the sensitivity of results to variations in solar wind conditions and computational resolution
- **Real time use**: Investigate real time delivery of simulation results to space weather operators

Fiscal Year Funding Summary ($K):

	In House	Capital Equip. (> $5,000 each)	Subcontractor	Total
FY 1999	$43,896		$16,000	$59,896
FY 2000	$25,000		$25,000	$50,000
FY 2001	$128,262		$25,000	$153,262

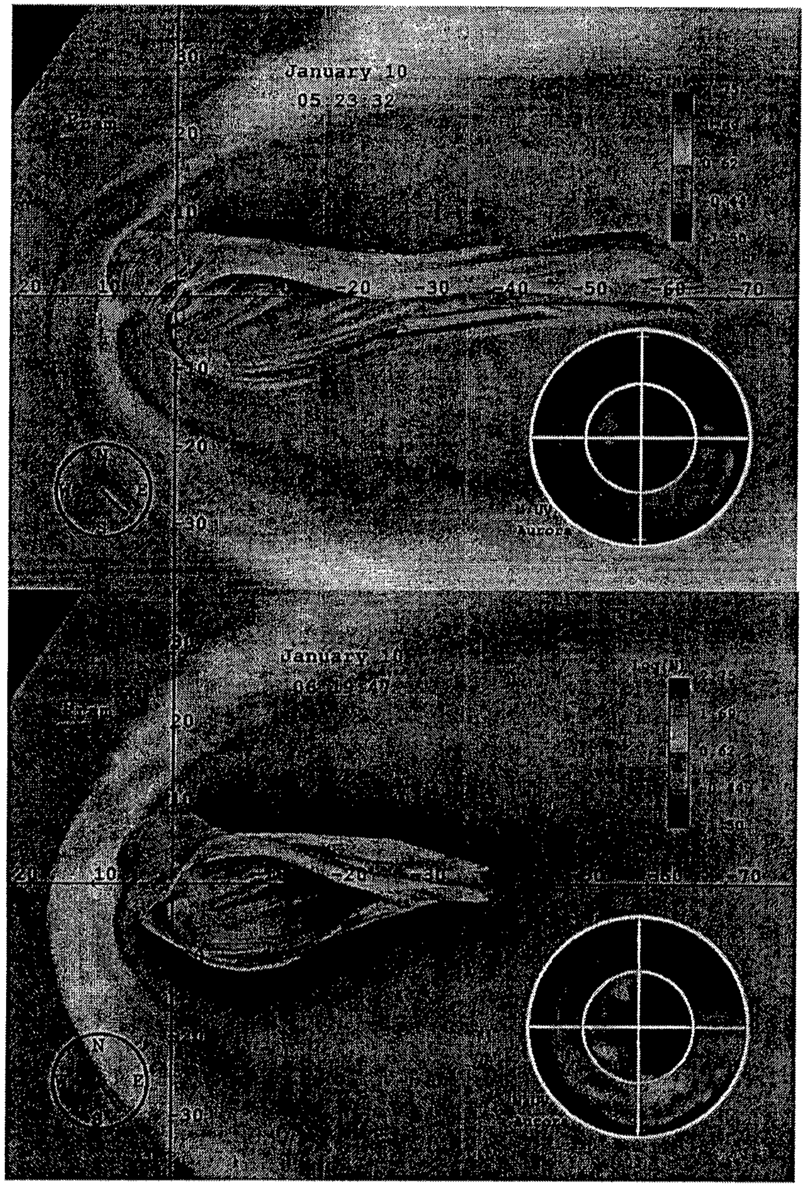
Summary of Progress:

In this three year project, we have investigated the feasibility of using the Lyon-Fedder-Mobarry (LFM) code to predict in real time space weather conditions and display these conditions through diagnostics tailored for the use of NOAA and Air Force operators. We have performed numerous simulations of diverse space weather events including magnetic storms and substorms using as input solar wind and IMF data from the WIND and ACE spacecraft. We have validated these results against spacecraft and ground based observations both in our own studies and through participation in community code metrics studies. We have also developed diagnostics for space weather operators that display the simulation results effectively and meaningfully. We have consulted frequently with our colleagues at the NOAA Space Environment Center throughout the project to get their evaluation of the diagnostics and presented them in papers each year at the Space Weather Week meeting they host.

In the first two years of the project we focused on validations studies of the LFM code and initial development of diagnostics. We began our validation effort through long duration simulations performed of magnetic storm events, which have had particular space weather impact. We have successfully compared our results with observations for several events. Our simulation of the January 1997 magnetic storm is a representative and particularly interesting example. Goodrich *et al.* (1998) performed the longest simulation done to date covering a period of over 36 hours) to model the magnetic cloud event of January 10-11, 1997 first seen as a coronal mass ejection by SOHO on January 6th. This event was notable for tracking of the event all the way from the Sun's surface to the Earth and for the extreme compression of the magnetosphere during the passage of the backside of the cloud. Our simulation modeled the activity in both the magnetosphere and ionosphere with surprisingly good agreement with both ground based and spacecraft observations. The simulation results show the importance of both the solar wind magnetic field and density in determining the structure of the magnetosphere and the activity in the ionosphere during the entire magnetic storm.

Three new results have come from this simulation that are particularly relevant here. First we found a strong correlation between the solar wind density N and ionospheric activity during the initial portion of the storm (0500-1500 UT). Figure 1 (from Goodrich *et al.* (1998)) shows snapshots of magnetospheric structure and ionosphere emission from 0500 to after 0700 UT. The lack of intense

ionospheric activity in the simulation for almost 2 hours after the southward turning at 0510 UT is clearly due to the unusually low value of N in this period. The beginning of intense activity at 0655 UT and the later intensifications at 0730, 0840, and 1100 UT are all due to significant density increases. This indicates the magnetosphere was strongly stressed and directly driven from 0500-1500 UT, and that the kinetic energy of the solar wind (not just the dayside merging rate) was a critical factor in determining the energy transfer from the solar wind to the magnetosphere. This result is supported by the ground observations. Radar observations of ionospheric activity reported by Sanchez et *al.* (1988) correspond very well our ionospheric results. The CANOPUS data [G. Rostoker, personal communication, 1998] and the magnetometer data assembled by Shue and Kamide (1998) show the onset of intense ionospheric activity just before 0700 UT, as seen in the simulation. Shue and Kamide have calculated the correlation between N and ionospheric activity in their collection of magnetometer data for January 10. They find little correlation before 0530 UT but a strong correlation thereafter. It is most likely that the correlation between N and the strength of the ionospheric electrojets is due to the unusually strong southward IMF during this period.



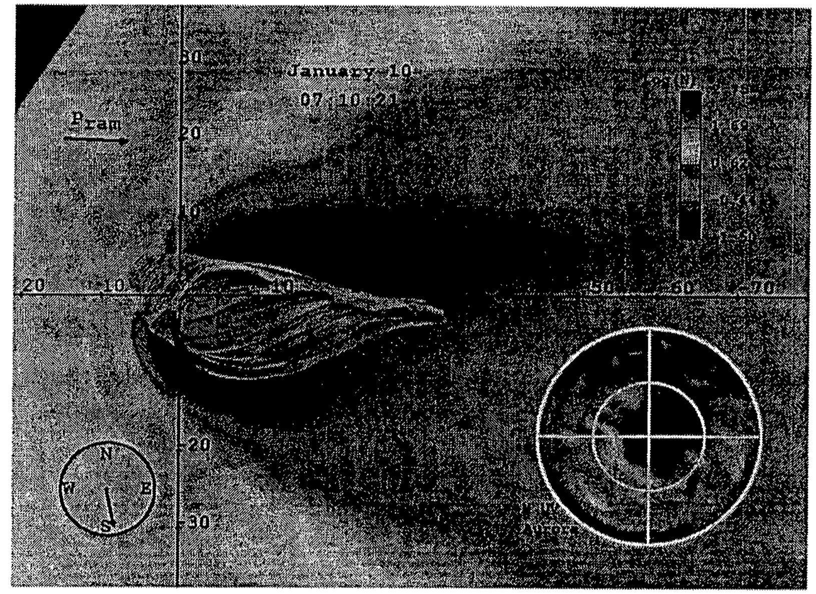
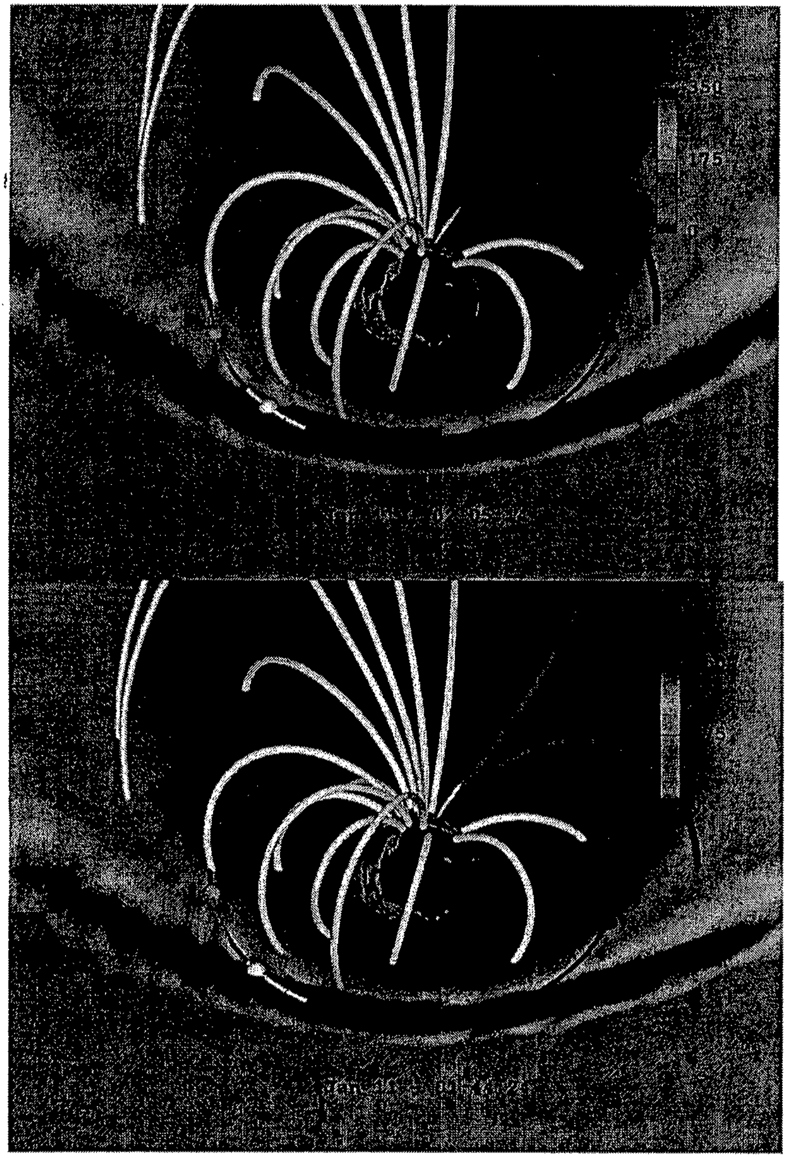


Figure 1: The log of plasma density in the noon-midnight plane from the simulations at (a) 0524 UT, (b) 0619 UT, and (c) 0710 UT on January 10. The boundary of the close field region is shown as a translucent 3D surface. UV emission in the northern hemisphere, > 45 deg Latitude, calculated from the simulation is shown in the MLT at the lower left; noon is at the top of the insert. The upstream IMF direction and magnitude (compass) and ram pressure (vector) are also present.



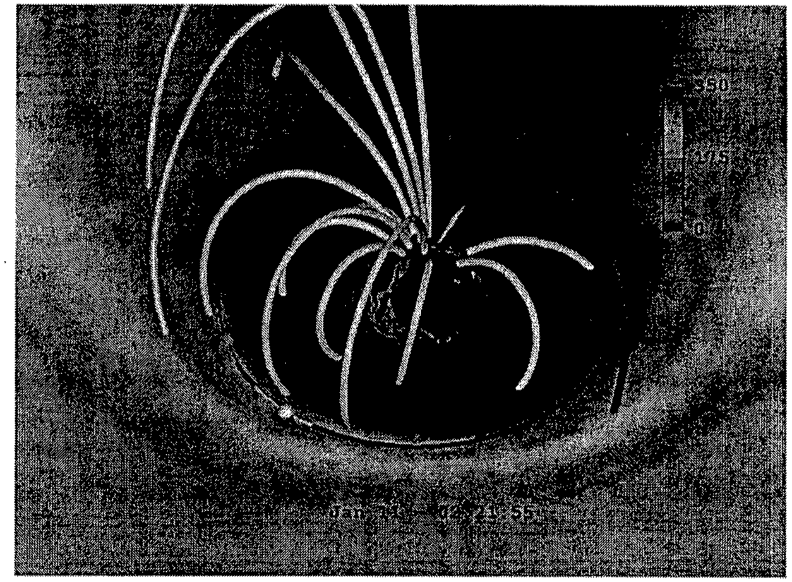


Figure 2: Views of the plasma density in the equatorial plane at (a) 0144 UT, (b) 0205 UT, and (c) 0221 UT. Closed (white) and open (orange) field lines are also included. The black circle depicts geosynchrous orbit. The positions of LANL satellites 1994-084 (white) and 1991-080 (yellow) as well as GOES-9 (purple) throughout this period are also shown.

Second, the simulation accurate predicted accurately the location of the magnetopause during the impact of the high density plasma filament trailing the magnetic cloud (about 0200 UT on Jan 11). As shown in Figure 2, the dayside magnetopause moved well within geosynchronous orbit. The figure shows the positions of the LANL 1994-084 (white), 1991-080 (yellow), and the GOES 9 (orange) satellites as well. At 0144 UT the magnetopause in the simulation had been pushed inward of LANL 1994-084, which stayed in the magnetosheath until 0221 UT. LANL 1991-080 and GEOS 9 remained within the magnetosphere. Reeves *et al.* (1998) have reported that LANL 1994-080 actually entered the magnetosheath 10 minutes later at 0154 UT and remained there until 0217 UT. Furthermore GOES 9 and LANL 1991-080 remained in the magnetosphere, though the latter approached, but did not cross the magnetopause, at 0212 UT.

Finally, Hudson *et al.* (1999) have recently analyzed the simulation electric field in the inner magnetosphere during an observed increase of relativistic electron flux over several hours (0900 - 1200 UT). They found the simulation field were from ULF waves with periods commensurate with the drift periods of electrons in the 0.2-3.2 MeV range in the region from 3-9 Re in the equatorial plane. These ULF waves thus can continuously accelerate electrons to MeV energy, and are the likely source of the relativistic electron flux observed during this period. This result suggests the amplitude of ULF waves in the code could provide an indicator for the presence of enhanced energetic electron fluxes, which is an important factor for the health of spacecraft in geosynchronous and lower orbit.

In addition, we have participated in several community code evaluations. We took part in the Electrojet Prediction Challenge for Space Weather Week 2000, sponsored by SEC as a means of testing the capabilities of various electrojet prediction models under the same conditions and with the same validation metrics. The SEC selected the March 19-20, 1999 interval, a period with relatively simple solar wind conditions, as the initial test bed for methods of predicting the strength and location of the auroral electrojets. The challenge consisted of predicting the ground magnetometer response using a real-time model driven by ACE solar wind observation and/or real-time magnetometer stations geographically isolated from the target stations. The LFM code was run in a real time mode for the entire two day period. The currents extracted from the ionospheric portion of the simulation where used to calculate the ground magnetic perturbations with the computationally efficient implementation of the Biot-Savart Law developed by Kisabeth and Rostoker, 1977. During the 48 hours of the simulation we determined the magnetic field perturbations at 12 stations, 3 stations in the 210 chain (KTN, TIX, CHD), 4 CANOPUS stations (TALO, RANK, GILL, FSIM), and 5 Greenland stations (SVS, UPN, GDH, SKT, FHB). The predictions for the H component showed best agreement with observations at lower latitudes and a tendency to under predict the strength of substorms. The RMS errors for the H component ranged from 38 nT to 88 nT. The predictions for the E and Z components where generally weaker with RMS errors ranging from 22 nT to 104 nT. Analysis of these results also indicated that the simulated agreement with magnetometer stations was strongest in the afternoon sector. The results from this event study can be used as a baseline for quantifying the effects of solar wind variations, ionospheric resolution, and model improvements on the simulation results.

The Space Weather community identified September 2000 as Space Weather month. During this month a coordinated effort was undertaken to maximize the data collection by various resources, eg SuperDARN, Incoherent Scatter Radars (ISR), and to have models make predictions of magnetospheric response the solar wind input. We ran the LFM code using the ACE data for a period starting at 12 UT on September 11th and ending at 24 UT on September 24th. This interval included several high density regions and a magnetic cloud passage as well as several ISR world days. Comparisons showed a weak agreement between the ionospheric convection patterns modeled from the SuperDARN observations and those obtained from the LFM ionospheric portion of the LFM code. This study also indicated the need to develop a more quantifiable method of comparing the results from the LFM with the electric field measurements of SuperDARN. Comparisons with the magnetometer stations within the CANOPUS networks on September 12th indicated a similar level of agreement with that obtained for the Electrojet prediction challenge. During one of the high density periods on September 12th, comparisons with geostationary observations indicate the simulation did a good job of predicting magnetopause cross of geostationary orbit. This simulation represents one of the longest MHD simulations ever completed and our analysis of the results is only in the preliminary stages.

At the end of the project's second year, we gave a single processor version of the LFM to SEC for testing in the Rapid Prototyping Center. We have helped them get the code compiled on their computer systems and have given Terry Onsager guidance on it use They are currently familiarizing themselves with the operation of model and evaluating its uses within their system. This is the first step in our plans to real time computational tests at SEC.

In the final year of our project, we concentrated upon further validation studies and working with the SEC staff to transfer the LFM code to them.

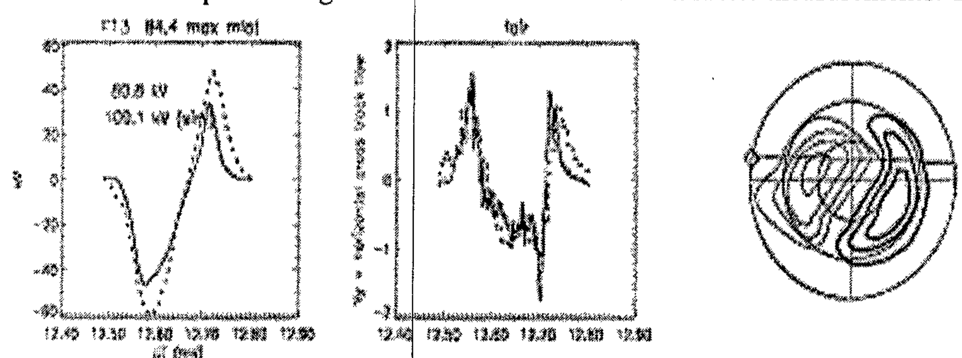
The parallel code was ported to the SEC Beowulf system. However, apparent compiler problems – which were consistent across a large number of local Beowulf clusters and x86 clusters at the NSF national centers – prevented our producing an executable that would run in anything but un-optimized mode. This was not sufficiently fast to be of use for the intended purpose. We were, however, able to demonstrate real-time operation at Space Weather Week in 2001. Because of the limited success in delivering a real-time code to SEC, we shifted our effort toward developing graphic tools for the delivery of code results to SEC and to the community at large. This has resulted in the development of a set of tools based upon the OpenDX visualization package.

We gave a demonstration at the past Space Weather Week at SEC of a real-time simulation of the magnetosphere using a new set of web based tools for transmitting and visualizing the simulation data to remote sites. The real-time run was accomplished using 8 SGI Origin processors at Dartmouth and was driven by ACE data picked up from the SEC site. The web-based tools are based upon OpenDX. This package is open source and allows the creation of Java applets, which can produce local interactive displays by interacting with the remote data server. Both the real-time capability and the interactive display capability are important for the interaction operations staff with models that may be running remotely. OpenDX provides us with an extensible set of modules and

tools based on a robust commercially developed software base that can be freely shared with our target user community. Particularly pertinent to this project is the ability of the Java based web tools to control as well as display results from visualization networks running on remote computational servers. This allows us to create operational control panels to view not only real time visualization results but also to aggregate "recent" results into animations, strip chart style time series recorders, and specialized operational analysis tools. The full set of tools needed for a complete space weather reporting system have not been developed, but we have finished a provisional set of tools which have been packaged into a OpenDX distribution which has been delivered to SEC, as well as to the Space Weather Community as a whole.

Our validation efforts were mostly directed at coordinated Space Weather community studies, and in particular, at the question of convection electric fields, which was visited in more detail through the GGCM Convection Challenge. Three periods were chosen for modeling. Each had a relatively constant or slowly varying solar wind and a number of DMSP satellite passes. We participated with a number of groups in this challenge; an overview of the results was given at the past Space Weather Week by Michael Hesse in his capacity as director of the Coordinated Community Modeling Center (CCMC). The general run of results showed that the average error coming from the MHD models of all participants was slightly better than a model, which presumed no electric field. The results from the LFM code showed a majority of extremely good agreements. While all the skill scores were variable depending on the particular DMSP pass, the LFM code showed the highest recorded skill scores. Figure 3 shows a typical comparison from the December 10, 1999 period. Plotted are the cross polar potential along the satellite track, the transverse electric field and the ionospheric potential pattern from the MHD simulation. The fit to the electric field is extraordinarily tight with the boundaries occurring in almost exactly the same places. A number of computed passes show behavior that mimics the DMSP data, but the boundaries are displaced. The Convection Challenge used average error as the metric and with this metric the displaced boundaries can give a value, which is as large as that from no electric field. However, one's intuition is that the model is actually much better than that. This illustrates the need to develop sophisticated metrics and methods of comparing simulation data against observation.

Figure 3. Comparison of the MHD electric field at ionospheric heights to the DMSP satellite drift meter measurements. The three panels show



the cross-polar potential along the track, the transverse electric field, and the MHD potential pattern, respectively. The DMSP results are the solid lines, the dotted lines are the MHD results. The potential pattern also shows the DMSP satellite track; the diamond indicates the start of the pass.

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Shue, J.-H. and Y. Kamide, "Effects of solar wind density on the westward electrojet", in Substorms-4, edited by S. Kokobun and Y. Kamide, published by Terra Scientific Publishing Company Kluwer Academic Publishers, 677, 1998.

Appendix A: In-house Activities

Instructions: Provide all information identified below for the last FY only. "Personnel" should include each scientist or engineer who contributed to the research during the year. Publication of articles derived from the research should be listed chronologically in bibliography format. Attach reprints. List only invention disclosures derived from this specific research effort. Honors may include recognition both inside and outside the academic and Air Force science & technology (S&T) communities. Extended scientific visits may include collaboration with other research programs, both foreign and US.

Personnel:

	Name	Degree	Discipline	Involvement
In House Employees	Charles Goodrich	Ph.D.	Physicist	1 month
	Michael Wiltberger	Ph.D	Physicist	1 month
Subcontractors	John Lyon	Ph.D.	Physicist	1.25 month
Visitors				

Publications:

Published in Peer Reviewed Journals and Books

Wiltberger, M., J. G. Lyon, and C. C. Goodrich, "Results from the Lyon-Fedder-Mobarry Global Magnetospheric Model for the Electrojet Challenge," Atmos. Solar Terr. Phys., in press 2002.

Arceo, R, R. E. Lopez, M. Wiltberger and J. G. Lyon, "Polar Cap Potential during Magnetic Storms: MHD Simulations," {\em Adv. Sp. Res.}, submitted 2002.

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Shao, X., P. N. Guzdar, G. M. Milikh, K. Papadopoulos, C. C. Goodrich, A. Sharma, M. J. Wiltberger and J. G. Lyon, "Comparing ground magnetic field perturbations from global MHD simulations with magnetometer data for the 10 January 1997 magnetic storm event", {\em J. Geophys. Res.}, 107(A8)10.2000JA000445, 2002.

Wing, S., D. G. Sibeck, M. Wiltberger, and H. Singer, "Geosynchronous magnetic field temporal response to the solar wind and {IMF} variations," {\em J. Geophys. Res.}, 107(A8)10.1029/2001JA009156, 2002.

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Wiltberger, M., T. I. Pulkkinen, J. G. Lyon, and C. C. Goodrich, "MHD Simulation of the Magnetotail During the December 10, 1996 Substorm," {\em J. Geophys. Res.}, 27649-27663, 2000.

Lopez, R. E, M. Wiltberger, J. G. Lyon, C. C. Goodrich, and K. Papadopoulos, "MHD Simulations of the Response of High-latitude Potential Patterns and Polar cap Boundaries to Sudden Southward Turnings of the Interplanetary Magnetic Field," {\em Geophys. Res. Lett.}, 967-970, 26, 1999.

Lopez, R. E., C. C. Goodrich, M. Wiltberger and J. G. Lyon, "Simulation of the March 9, 1995 Substorm and Initial Comparison to Data," in Geospace Mass and Energy Flow: Results from the International Solar-Terrestrial Physics Program, AGU, Geophysical Monograph 104, 237-245, 1998.

Lyon, J., R. E. Lopez, C. Goodrich, M. Wiltberger, and K. Papadopoulos, "Simulation of the March 9, 1995 Substorm: Auroral Brightening and the Onset of Lobe Reconnection," {\em Geophys. Res. Lett.}, 25, 3039-3042, 1998.

Goodrich, C. C., M. Wiltberger, R. E. Lopez, K. Papadopoulos and J. G. Lyon, "An Overview of the Impact of the January 10-11, 1997 Magnetic Cloud on the Magnetosphere via Global MHD Simulation," {\em Geophys. Res. Lett.}, 2537-2540,

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Goodrich, C. C., M. Wiltberger, R.E. Lopez, K. Papadopoulos, and J.G. Lyon, "An overview of the impact of the January 10-11, 1997 magnetic cloud on the magnetosphere via MHD simulations", Geophys. Res. Lett., 25, 2537, 1998.

Hudson, M.K., S.R. Elkington, J.G. Lyon, and C.C. Goodrich, "Increase in relativistic electron flux in the inner magnetosphere: ULF wave mode structure", Adv. Space Res., 25, 1327, 2000.

Invention Disclosures and Patents Granted:

Invited Lectures, Presentations, Talks, etc.:

Goodrich, C. C., J. G. Lyon, M. J. Wiltberger and R.E. Lopez, "Interaction between the inner and mid-tail regions in MHD simulations of substorms", presented at the presented at the AGU Fall Meeting in San Francisco, CA, 1999.

Lopez, R.E., M. J. Wiltberger, J. G. Lyon, and C. C. Goodrich, "MHD simulations of the response of the high-latitude potential patterns and polar cap boundaries to sudden southward turnings of the interplanetary magnetic field ", presented at the AGU Fall Meeting in San Francisco, CA, 1999.

Wiltberger, M, J. G. Lyon, and C. C. Goodrich, "MHD Simulations of the Earth's magnetosphere with virtually no solar wind", presented at the presented at the AGU Fall Meeting in San Francisco, CA, 1999.

Wiltberger, M, J. G. Lyon, and C. C. Goodrich, "Results from the Lyon-Fedder-Mobbary Global Magnetospheric Model for the Electrojet Challenge", presented at the Space Weather Week Conference in Boulder, CO, 2000.

Wiltberger, M., J. G. Lyon, and C. C. Goodrich, "Space weather forecasting with a global MHD code", presented at the NATO-ASI on Space Storms and Space Weather Hazards in Crete, Greece, 2000.

Wiltberger, M., J. G. Lyon and C. C. Goodrich, "Magnetospheric Nowcasting via a Global MHD simulation", presented at the Chapman Conference on Space Weather in Clearwater, FL, 2000.

Wiltberger, M. J. G. Lyon, C. C. Goodrich, K. Baker, and S. Shepard, "Results from global MHD simulations during Space Weather Month", presented at the Fall AGU meeting, Washington, DC, 2000.

Professional Activities (editorships, conference and society committees, etc.):

Honors Received (include lifetime honors such as Fellow, honorary doctorates, etc., stating year elected):

Extended Scientific Visits From and To Other Laboratories:

Appendix B: Off-Site Contract and Grant Activities

Instructions: Provide all information identified below for the last FY only. Publication of articles derived from the research should be listed chronologically in bibliography format. Attach reprints. List only invention disclosures derived from this specific research effort.

Publications:

Invention Disclosures:

Summary of Progress:

Appendix C: Technology Transitions/Transfers Detailed Listing

Performer *(name, telephone, and organization)*	**Customer(s)** *(name and organization)*	**Research Result** *(scientific statement)*	**Application** *(technical benefit(s) and/or customer use– List and underline any military applications first)*	Transitioned To	Transitioned From	Application
John G. Lyon 606-646-1242 Dartmouth College	Terry Onsager 303-497-5713 SEC	Single Processor LFM code	Real time simulation Of the earth's magnetosphere	A	O	PD

Note: In the last three columns enter the following codes:

Transitioned From:
- AFRL = L
- Industry = I
- Academia = A

Transitioned To:
- Industry = I
- Air Force 6.2 or 6.3 = AF
- Other AF, DoD, or Government = O

Application:
- Product (New or Improved) = Pd
- Process (New or Improved) = Pc
- Other Technology Benefit = O